

Electric Propulsion for the Psyche Mission

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NASA's Psyche mission will launch in 2022 and begin a 3.5-year cruise to the metallic asteroid Psyche, where it will orbit and examine this unique body. All primary propulsion for the mission will be done with the Maxar SPT-140 system; this will be the first use of Hall thrusters for a NASA mission and the first time they will be used beyond cis-lunar space. The electric propulsion system architecture and its usage for the Psyche mission are described here, along with the modifications to the commercial Earth-orbiting system that are required for deep-space operation. Recent efforts for system development have included thruster plasma diagnostics in support of modeling activities, component development testing, system integrated testing, thruster in-flight performance model development, and thruster life validation. The status of all of these activities is discussed here. Of particular note are the challenges to throttle curve development caused by facility effects on thruster performance as well as the effects of thruster aging, and life validation activities aimed at bridging the gap between the as-performed thruster life test and the Psyche-mission-specific environments and thruster operating conditions.

I. Introduction

Psyche is the latest in the series of NASA Discovery Exploration Missions over the past twenty-seven years that have included NEAR, Mars Pathfinder, Lunar Prospector, Genesis, Deep Impact, Stardust, Kepler, GRAIL, MESSENGER, Insight, and Dawn's journey to Vesta and Ceres. The Psyche mission will use solar electric propulsion and a Mars gravity assist to rendezvous with and orbit the largest metal asteroid in the solar system, called (16) Psyche. Once there, it will spend nearly two years in a series of four decreasing-altitude orbits studying its topography, gravity, magnetism, surface features, and material characteristics.

The asteroid Psyche was originally discovered in 1852 and is a unique body in the solar system. It is the largest Class-M asteroid known with a mean diameter of about 210 km, and based on optical and radar investigations from Earth is composed of over 90% iron and nickel. The leading hypothesis for Psyche's formation is that it is the differentiated metal core from a planetesimal that was forming in the region between Mars and Jupiter, but was

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destroyed by multiple “hit-and-run” collisions early in the solar system’s formation that stripped the silicate mantle and left some or nearly all of the metal core behind. Determining if the asteroid Psyche is truly an exposed planetary core is the primary goal of the mission.

The Psyche investigation has three broad goals: (1) understand a previously unexplored building block of planet formation: iron cores; (2) look inside the terrestrial planets, including Earth, by directly examining the interior of a differentiated body, which otherwise could not be seen; and (3) explore a new type of world: for the first time, examine a world made not of rock or ice, but of metal. To achieve these goals within the constraints of a Discovery Mission, the Psyche spacecraft will deliver a domestic science payload into Psyche orbit that consists of two multispectral imagers (cameras), two magnetometers, and a gamma ray and neutron spectrometer (GRNS). In addition, Psyche will fly a technology demonstration instrument called Deep Space Optical Communications (DSOC) to demonstrate high data rate communications deep into the solar system. The multi-year science investigation will characterize Psyche’s size and gravity field, measure any residual magnetic field expected if Psyche is really a core, and determine its composition and surface characteristics. Of great interest is the surface topography of an all metal body that has experienced numerous impacts that produced unique cratering shapes and characteristics and deposited other materials on the asteroid surface.

The spacecraft bus is based on a “Solar Electric Propulsion (SEP) Chassis” provided by Maxar (formerly SSL), a leading manufacturer of geosynchronous communications satellites. The SEP Chassis includes the primary spacecraft structure, a 10-panel 20-kW solar array (at 1 AU), and a high-power electric propulsion (EP) system based on the flight-proven SPT-140 Hall thruster. Maxar has launched and successfully operated over 150 Hall thrusters as of August 2019. Maxar is also responsible for the 100-V power system running the EP system and powering the rest of the spacecraft, the thermal control system, the attitude and control system (ACS) hardware, and a nitrogen cold gas propulsion system used for safe mode control of the spacecraft and some momentum unloading in the science orbits. The Maxar power system uses a unique architecture of shunt regulators, boost converters and battery chargers to optimize the power provided to the spacecraft loads for science and propulsion at Psyche. JPL is responsible for the command and data handling (C&DH) avionics hardware, the X-band telecom system for communicating with NASA’s Deep Space Network, all the flight and guidance and navigation control (GNC) software, and the autonomous fault protection system.¹⁻⁴ The Psyche Project passed its Preliminary Design Review (PDR) in early 2019, and is now in Phase C of the development proceeding toward Critical Design Review.

II. Electric Propulsion System Usage

Psyche’s electric propulsion (EP) subsystem will be used for four distinct mission purposes: interplanetary cruise from Earth to the asteroid Psyche, spacecraft momentum management during cruise, transfers between the science orbits at the asteroid, and orbit maintenance at the asteroid. Only one thruster will be operated at a time – the commercial spacecraft product line has the capability to operate multiple thrusters simultaneously, but the adverse impact to Psyche’s thermal management design was determined to outweigh the mission benefits of dual-thruster operation.

Following an August 2022 launch the spacecraft begins a three-year cruise that includes a Mars gravity assist in May 2023. After a short approach phase the spacecraft will be captured into Psyche orbit in January 2026 at 2.7 AU from the Sun and begin the science phase of the mission. Four different asteroid orbits, with progressively lower altitudes, are planned to meet the mission science objectives. The science mission concludes in October 2027.

Interplanetary cruise trajectory analysis is performed with the Mystic software which was also used for the Dawn mission. For the baseline mission design as of Project PDR, an Atlas V-411-class

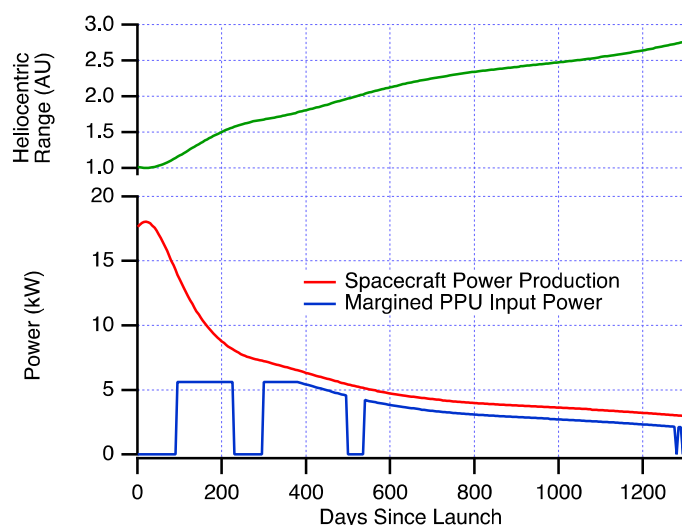


Fig. 1. Psyche Cruise Trajectory Range and Power.

launch vehicle is assumed. The cruise to the asteroid follows a simple outbound trajectory as shown in Fig. 1. The analysis assumes end-of-life power production (a current-best-estimate of about 18 kW at 1 AU) and 900 W of power required to operate the spacecraft bus throughout the cruise. A power margin of 12% was also applied to the PPU input power to account for uncertainties in power production and EP system consumption as well as missed thrust.⁵ Thrusting with the EP system begins at full thruster power after the 90-day post-launch spacecraft checkout phase and ceases prior to the Mars gravity assist window. Thrusting resumes and then, about 400 days after launch, the spacecraft is far enough from the sun that it does not have sufficient power to thrust at full thruster power. From this point forward the EP system is throttled down to operate at the maximum available power. With the exception of a short optimal coast period near 500 days the EP system thrusts continuously until capture into science Orbit A. At this point, the thruster discharge power used in the trajectory is about 1.7 kW.

The EP system does not actually thrust continuously throughout the operational portions of the cruise phase. The trajectory analysis assumes a thruster duty cycle of 80% from Earth to Mars and then 90% after Mars until asteroid approach, where a 50% duty cycle is assumed for the remainder of the mission. This is modeled by Mystic, for example, as continuous thrusting at 80% of the full thrust value from Earth to Mars. These non-thrusting portions of the trajectory account for spacecraft operations such as ground communications, DSOC operations, and reaction wheel momentum unloads.

The spacecraft attitude during cruise will be controlled in all three axes using the reaction wheel assemblies. The primary disturbance to attitude will be the swirl torque produced by SPT-140 thruster operation which is estimated⁶ to be about 300 $\mu\text{N}\cdot\text{m}$ at full power, decreasing roughly linearly with thruster power throughout the mission. Every few days, a short (~10 min) thruster firing will be performed using a different thruster on the opposite side of the spacecraft to unload the stored momentum in the wheels. Since the swirl torque produced by the thruster likely will not be known prior to the flight, there is some uncertainty in the frequency and duration of these swirl unload operations.

Once at the asteroid the EP system will be used mainly for transfer between the science orbits. About three weeks of thrusting each are required for the transfer from Orbit A to Orbit B, and from Orbit B to Orbit C. Transfer from Orbit C to the 85-km-altitude Orbit D requires an orbital plane change and 4.5 months of thrusting. During this transfer the spacecraft begins to encounter eclipses which last through the entirety of Orbit D. Thrusting with the EP system is not planned during eclipse periods.

Overall EP system throughput for the deterministic thrusting during cruise and proximity operations is depicted in the propellant usage histogram of Fig. 2. Total thrusting time for all thrusters is ~23 khr. Contrary to the commercial implementation which operates mostly at 4.5 kW with some operation at 3.0 kW for stationkeeping, the bulk of thruster operation for Psyche will occur between roughly 1.5 and 3.5 kW. This has impacts for thruster life validation, which will be discussed later in Section VI. Allocations for deterministic and non-deterministic thrusting are shown in the xenon propellant budget in Table 1, along with allocations for presently-held margins and non-useable propellant. Most of the non-useable propellant is allocated for extensive system checkout after launch. Propellant margin is

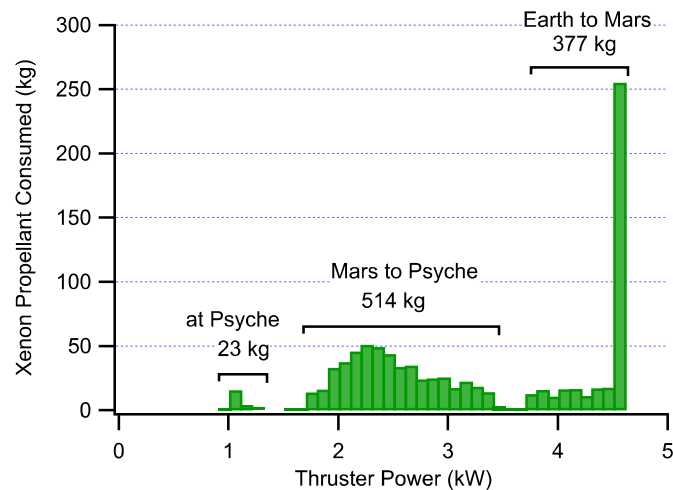


Fig. 2. Thruster Throughput for Baseline Trajectory at Project PDR.

Table 1. Xenon Propellant Budget at Project PDR.

Usage Category	Propellant Allocation, kg
Deterministic Cruise	885.0
Cruise Momentum Management	5.0
Capture to Orbit A	6.4
Orbit Transfer: A to B	2.4
Orbit Transfer: B to C	1.8
Orbit Transfer: C to D	15.8
Orbit Maintenance	2.5
Non-Usable Propellant (residuals, leakage, fill error, thruster startup/shutdown, initial checkout)	38.9
Margin: Missed Thrust	35.4
Margin: Thruster Performance Uncertainties	36.8
Total	1030.0 kg

upstream solenoid valve, a proportional flow control valve, three orifices to control the cathode-to-anode flow split, and a dual-flow path with an additional solenoid-type latch valve that allows for different flow splits at different thruster power levels. The solenoid valves and the proportional control valves are commanded by either of the PPUs; the pyrotechnic valves and the latch valves in the PMA and the XFCs are actuated by the spacecraft.

The XFCs and thrusters are integrated onto a dual-axis gimbaling module that allows for thrust vector articulation throughout the mission. Two thrusters, each with their own XFC, are mounted on each of two modules as shown in Fig. 5. The assemblies, named DSMs (Dual-Axis Positioning Mechanism for Stationary Plasma Thruster Module) are located on opposite sides of a spacecraft for five degree-of-freedom control. Each actuator can move independently, and regardless of whether or not a thruster is firing.

As a whole, the EP System is single-fault tolerant with the exception of the propellant tanks and lines and with respect to a mechanical fault in one of the DSM actuators (the actuators are electrically redundant). Only one PPU and three thrusters are required to complete the mission.

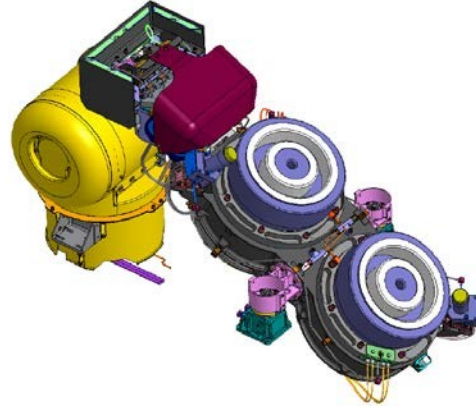


Fig. 5. Thruster Gimbal Module (i.e. DSM).

B. Modifications to Commercial Heritage Designs

Much of the heritage system can be used for Psyche without any modifications. For example, the thruster, PMA, DSM actuators, and xenon tanks are used as-is. The expanded throttle range and low-power operation requirements, however, do require significant modifications to the XFC and PPU. There is also a minor part change in the TASU.

XFC Modifications

Maxar and Moog have developed a new Xenon Flow Controller (XFC) to meet the more demanding requirements of the Psyche Mission.⁸ Maxar's heritage XFC-140 is required to operate within a flow rate range of 11 to 16 mg/s in order to span a thruster discharge power range of 3.0 to 4.5 kW.⁹ The XFC-140 includes a thermothrottle to control the total propellant flow, a set of orifices to split the flow between the anode and cathode lines, and three solenoid valves to provide upstream and downstream flow isolation. The set of orifices is fixed and provides a cathode-to-anode flow split ratio of about 5% throughout the full range of required flow. The Psyche mission instead has different requirements because the EP system will need to operate from 1 AU up to 3.33 AU from the Sun where there is a limited amount of power available to the propulsion system. The SPT-140 is thus required to operate between 0.9 kW to 4.5 kW, and this larger power range requires a larger propellant flow rate range spanning from about 5 to 16 mg/s. It also requires a variable cathode-to-anode flow split to facilitate operation at lower thruster powers. These operational characteristics could not be achieved with the heritage XFC design.

The new XFC, shown in Fig. 6, is an assembly of flight-proven components: a proportional flow control valve (PFCV) used to adjust the total propellant flow rate; three orifices used in two different combinations at two different power ranges; a latch valve to open a flow path to one of the orifices; and a normally-closed solenoid valve as a second point of flow isolation. The PFCV is also a normally-closed solenoid valve, for which the outlet opening depends on the amount of current passing through the solenoid coil. This design allows the flow rate to be controlled over a wide range of flow rates; the specific range depends on the upstream and downstream pressures, which depend on the orifices and other constrictions in the flow path. In the Psyche configuration the XFC is designed to operate between 3 and 23 mg/s in order to provide enough margin against the system requirements. A peculiarity of the PFCV is the hysteretic behavior: the current required to achieve a specific flow rate depends on the way the set current

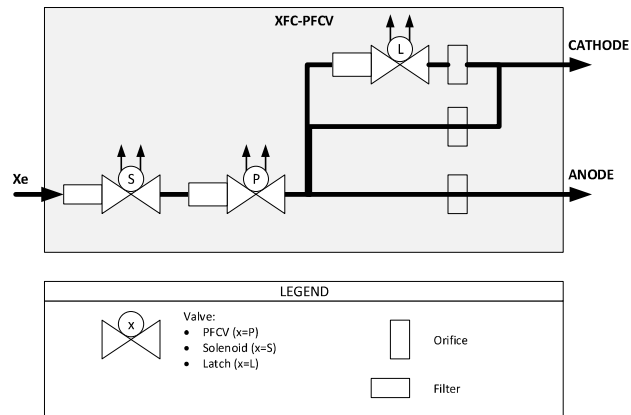


Fig. 6. Psyche Xenon Flow Controller Schematic.

is approached.¹⁰ It is also worth noting that the PFCV characteristics change with temperature because the resistance of the solenoid is affected, however this variation is limited when operating at the nominal temperature of 20 ± 10 °C. The anode and cathode orifices set the cathode-to-anode flow split ratio. Earlier studies¹¹ led to Psyche requirements for different flow splits at different discharge power ranges: a flow split of 5% is required at higher power levels (>1.5 kW), while 9% is required at lower power levels (< 1.5 kW) to limit the cathode-to-ground voltage. The larger flow split is achieved by opening a parallel cathode line to introduce an additional orifice in the cathode flow path, which effectively increases the cathode orifice size and changes the flow split from 5% to 9%. More information on the design guidelines of the new XFC and its components, as well as the results of unit testing and system level testing, can be found in a companion paper.⁸

PPU Modifications

Several design modifications to the Maxar heritage PPU-140 are planned for the Psyche PPU. The major changes are to the propellant flow control circuit (i.e. PFCV driver) and the addition of a steady-state cathode keeper current capability for low-power operation. These changes also necessitated modifications to the PPU control logic and telemetry. A summary is given below, and further details can be found in a companion paper.¹²

PFCV Driver

The PFCV driver circuit is derived from the circuit used to control the thermothrottle that is utilized in Maxar's heritage XFC-140.⁹ Both circuits are part of a closed-loop system responsible for controlling the amount of gas flow in order to regulate the discharge current, but the manner in which this is accomplished is a significantly different. The heritage thermothrottle heating circuit is generated by a flyback converter topology. This design generates an error signal from the actual discharge current which is proportional to the output of the converter (i.e. the thermothrottle drive voltage). The PFCV driver generates an error signal through a similar integrator topology, but instead with a much longer time constant in order to gradually actuate the valve, as opposed to the much quicker response allowed by the thermothrottle. This error signal no longer sets a bias voltage for a flyback converter, but rather a second integrator stage. The 'inner' control loop regulates the PFCV current, and thus the amount of gas flow provided to the thruster.

Steady-State Cathode Keeper Current

The heritage PPU-140 provides 300 V pulses to the cathode ignitor (i.e. keeper) electrode at a rate of approximately 10 Hz in order to initiate the thruster plasma discharge, and then the ignitor power supply is turned off. For Psyche, when operating at thruster discharge powers less than 1.5 kW, this power supply needs to transition from high-voltage pulses to a steady-state keeper discharge instead of turning off at thruster ignition. This is implemented with a bi-level signal input to the ignitor circuit which converts the control loop from a voltage regulation for the 300 V pulses to a pseudo-power regulation for a constant 17-26V output to the keeper electrode.

PPU Control Logic

Most PPU control logic is retained from the heritage PPU, for example the startup and operating commands, system startup timing, and system cross-strapping controls. Newly added is a separate 'low power mode' of operation; the 'high power mode' is equivalent to the heritage PPU mode of operation. In the low power mode, defined as a commanded discharge current setpoint of 5 A or less, the keeper power supply will operate in steady-state mode instead of turning off after ignition. In conjunction with this, a new discharge current threshold for fault handling has been created for the low power mode. Other fault handling processes and the fault flags remain the same for both modes.

Telemetry

For Psyche there are only minor changes to the heritage telemetry. Thermothrottle current will be replaced by PFCV current. With the addition of the keeper functionality, telemetry for the steady-state keeper voltage will be included, taking the place of thermothrottle voltage in the heritage design. All other telemetry such as discharge current, float voltage, relay status, etc. are retained from the heritage design.

TASU Modifications

The Thruster Auxiliary Support Unit (TASU) includes transient voltage suppression diodes for system electrostatic discharge protection. With the increased voltage in the PFCV driver circuit compared to the thermothrottle circuit, these diodes have been changed from 15-V parts to 32-V parts. There are no other changes to the TASU design.

IV. Development Testing

Several tests have been performed with the thruster, PPU, and XFC in order to understand the performance of the thruster and the system as it pertains to application for deep-space missions such as Psyche. Initial testing of the throttled performance of the SPT-140 beyond the commercial operating points of 3.0 and 4.5 kW was performed with the Development Model 4 (DM4) thruster.¹³ Those results showed that the thruster was capable of stable operation at discharge powers as low as 0.23 kW. Although the cathode-to-ground voltages became increasingly negative at the lower powers, additional cathode propellant flow rate and the addition of cathode keeper current mitigated this effect. Thruster performance was later verified on the Qualification Model 2 (QM002) thruster, and longer-duration stability at low powers was demonstrated with a 27-hour test at 0.8 kW.¹⁴ An integrated test with a modified PPU-140 demonstrated the ability to operate the PFCV and control the propellant flow rate over the range necessary for Psyche. As a final part of this early system work, the thruster life test on the QM001 unit was extended by operating it for 250 hours each at 0.9 and 1.0 kW then an additional ~480 hours at 4.5 kW.⁷

More recently, a series of tests were conducted to characterize the effects of test facility background pressure on the thruster performance over the power throttling range of the mission.¹¹ Thrust differences of between 3 and 7% were observed between the highest and lowest pressures characterized, except at the lowest power of 0.9 kW where no measurable thrust changes were found. Propellant flow rates did not show significant variation as facility pressure was changed. These data are needed to develop performance predictions of the thruster in space environments, and have also been used to validate models used to assess thruster life and performance as will be discussed later. Low-power operation tests were also performed that, in combination with other work, has defined the thruster operating conditions to be used for low-power operation and thus the subsystem hardware modifications described earlier. Specifically, a steady-state keeper current of 1.15 A and an increased cathode flow fraction of 9% were identified as the desired operating conditions for thruster power levels of 1.5 kW or less.

Development work has continued for the Psyche mission: a series of plasma diagnostic tests were conducted to gather data necessary for the Psyche thruster life validation work, a development model XFC was fabricated and tested, and this XFC was integrated with the thruster and modified EM PPU for a subsystem integrated test. This work is described in the sections below.

A. Laser-Induced Fluorescence Measurements

Like all existing Hall thruster modeling tools, JPL's Hall2De code¹⁵⁻¹⁷ requires experimental measurements of the plasma potential profile near the acceleration region in order to set the magnitude and spatial dependence of the non-classical ("anomalous") electron transport across the radial magnetic field. The preferred non-invasive method for obtaining this input data is to measure the ion velocity distribution function (IVDF) as a function of position using laser-induced fluorescence (LIF);^{18,19} once the ion velocities are known, the accelerating potential can be inferred.^{20,21} LIF measurements on an SPT-140 QM002 thruster were carried out at JPL in order to enable modeling of the thrust and channel erosion rate as a function of background pressure and magnet coil current.

The LIF setup was similar to that described elsewhere.^{20,22,23} An amplified tunable diode laser was used to selectively excite singly-charged xenon ions with a velocity component along the beam direction such that the Doppler-shifted photon wavelength seen by the ions was equal to 834.953 nm, and the resulting fluorescence emission was collected. Data were taken simultaneously along two orthogonal lines of sight rotated 45 degrees from the axial and radial directions, with ~1.5 mm spatial resolution. The injected beams were modulated at different frequencies to enable separation of the two

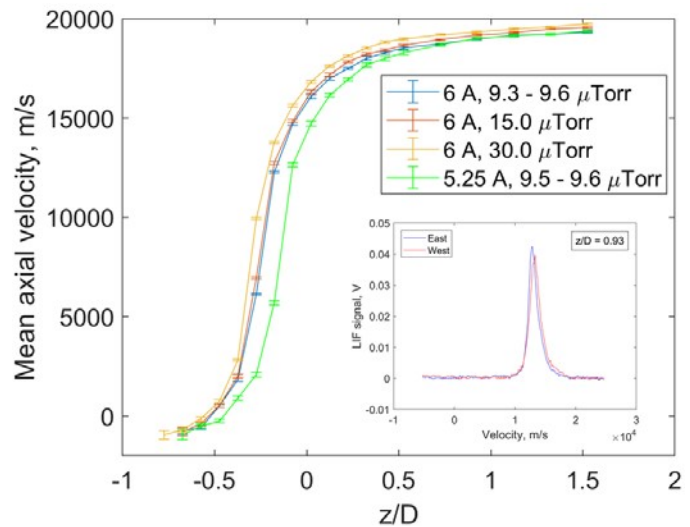


Fig. 7. Mean ion velocity vs. position along the channel centerline from LIF data. Results are shown for 4.5 kW operation with 6 A magnet current at three background pressures, and also at the minimum achievable pressure with 5.25 A magnet current. The inset shows an example of the measured IVDFs at one spatial location, from which the mean v_z was calculated.

signals using lock-in amplifiers, and the laser wavelength was scanned to map out the IVDFs along each direction. The mean velocity components were calculated from the first moment of each IVDF.²²

Fig. 7 shows the mean axial ion velocity as a function of position along the channel centerline for full-power (4.5 kW) operation. The position is given with respect to the thruster face and is normalized to the channel diameter D . The region around $z/D \approx -0.2$ where the velocity increases most steeply is the acceleration zone. Error bars on the mean velocity are derived from a bootstrap resampling analysis on the raw IVDF data.²² The dependence on background pressure was studied by injecting additional xenon flow toward the beam dump from a location downstream of the thruster.²⁴ The acceleration zone was located further upstream at higher background pressures, consistent with results from other Hall thrusters,^{20,25-27} including the SPT-100.²⁸ A larger downstream shift in the acceleration position was observed when the magnet coil current was reduced from 6 A (the nominal setting for Psyche) to 5.25 A (the life test setting). The ultimate velocity reached by ions in the near plume increased at higher background pressure, indicative of higher net ion accelerating voltage—this trend is responsible for a substantial part of the SPT-140's thrust increase at higher background pressure.^{16,17}

Fig. 8 compares the measured velocity vectors away from the channel centerline at the highest and lowest background pressures studied (for 4.5 kW operation). No measurable background pressure dependence in the vector directions (i.e., the beam divergence) was found at these near-field locations. Vector plots such as this one were used to validate the velocities predicted by Hall2De at off-centerline locations.

Beyond the results presented here, additional LIF data both on and off the channel centerline were acquired at operating powers of 4.5 kW, 2.5 kW, and 0.9 kW—comprehensive results will be presented in a forthcoming publication.

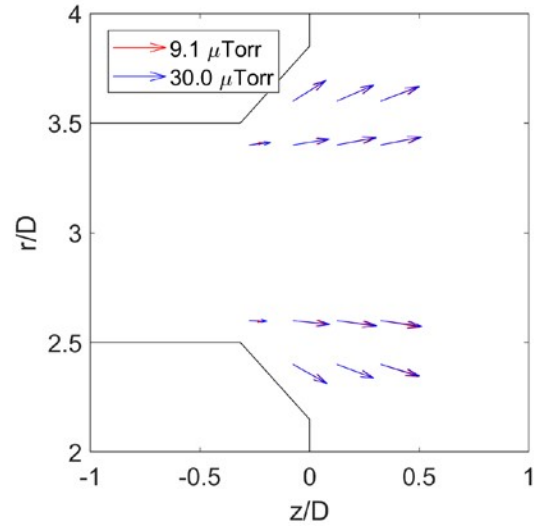


Fig. 8. Mean velocity vectors from LIF data for operation at 4.5 kW with 6 A magnet current.

B. XFC Development Testing

A development-model XFC was assembled at Moog from engineering-model components, and this unit was used for performance characterization and demonstration of compliance with requirements. The three flow orifices were manufactured using heritage processes and selected to provide the combination of flow range and cathode-to-anode flow split. Unit-level performance testing was conducted at temperatures of -10 °C, 21 °C, and 50 °C at a constant inlet pressure of 37 psia. In this testing the cathode-to-anode flow split was measured across a propellant flow range of 3 to 23 mg/s. The design was shown to provide the entire flow range, and the measured flow splits met the requirements within the experimental uncertainty, at all temperatures. Additional tests were conducted to determine the minimum XFC inlet pressure necessary to provide the minimum and maximum flow rates. At 21 °C, an inlet pressure of 5.2 psia was required to provide a total flow rate of 3.3 mg/s with a flow split of 9%. This low-pressure input allows for more xenon extraction from the tanks near the end of the mission and reduces the unusable propellant residuals.

Additional XFC unit-level testing was performed at JPL prior to and during the system integrated testing. First, propellant flow rates as a function of PFCV current were measured. This was necessary because the PPU startup process includes the initiation of propellant flow prior to thruster ignition by setting a fixed valve current. With no discharge current feedback before ignition, the flow must be controlled in an open-loop mode. These measurements included characterization of the valve hysteresis¹⁰ and also flow repeatability at a given current setting. During initial testing the valve current was increased from zero to the desired setpoint and this was found to yield very different flow rates from test-to-test in some cases. The valve opening procedure was changed to fully open the valve at first, then reduce the current to the desired setpoint. This method significantly reduced the variations in flow repeatability when in open-loop control and hence was implemented as a part of the standard startup procedure. Additionally, flow uncertainty as a function of valve temperature when in open-loop control was investigated and found to have a minor effect compared to the valve hysteresis effects. At the conclusion of these tests it was determined that the flow rates provided by the XFC were repeatable to within ~2 mg/s at a given PFCV current, using the valve startup method

described above and when the PFCV body temperature was maintained within 20 ± 10 °C. Additional description of the XFC development testing may be found in a companion paper.⁸

C. System Integrated Testing

A series of integrated subsystem tests were performed to validate at the system level the Psyche-specific changes that were made to the PPU, XFC, and TASU. The subsystem integrated test campaign was performed at JPL and consisted of three main objectives: 1) validate the XFC design, 2) validate the low-power operation mode of the PPU, and 3) validate the new XFC control circuitry. Each individual unit underwent component-level validation testing prior to the system test; the system testing was aimed at addressing component interactions together with a functioning thruster. This test was the first time that the XFC supplied propellant to an operating thruster and that the PPU controlled the PFCV. It was also the first time that the modified PPU ignitor power supply would ignite the thruster and low power and then sustain the keeper discharge. A summary of the integrated test is provided here; a full description of the test and results are provided in a companion paper.¹²

Testing was conducted with an engineering-model PPU and TASU, the development-model XFC, and the QM002 thruster in a flight-like configuration. Harness with flight-like construction and length was used between all components to represent the flight system as accurately as possible in a laboratory test. The test was divided into separate phases. First, the XFC and thruster were operated together with laboratory power supplies to verify XFC functionality. This testing was performed with the XFC located outside of the vacuum facility so that the individual anode and cathode flow rates could be measured. Following this test all of the components were assembled into the full system, with the XFC located inside the vacuum facility near the thruster and the PPU and TASU located immediately outside. System control was provided by a laptop computer that interfaced with the PPU and simulated the spacecraft command and control functions.

The XFC-thruster testing was performed first to verify the XFC functionality and also the cathode-to-anode flow split, which could not be done with the XFC located inside the vacuum chamber during the full system testing. Open-loop control of the PFCV current was provided with a laboratory power supply to control the thruster discharge current. The thruster was operated over the full range of powers for Psyche, and the XFC latch valve was actuated to provide the additional cathode flow rate at lower powers. All XFC functionality including the required cathode-to-anode flow splits was verified. Additionally, the open-loop performance of the PFCV was measured (i.e. flow rate vs. input current) for use in determining the startup parameters for full-system operation.

Next, the PPU low-power mode was tested with the full system configuration. The PPU low-power mode is defined by a discharge current setpoint of 5.0 A. At a setpoint above this value the keeper supply will be off, and below this value the keeper supply will sustain the keeper discharge. For this testing the PFCV was controlled in open-loop with an external power supply. Thruster starts into high-power and low-power modes were performed and the correct keeper function verified. Keeper currents of 1.1 to 1.6 A were measured at discharge power levels of 0.9 to 1.5 kW, respectively. System operation was additionally verified while throttling across the 5.0-A threshold while increasing and while decreasing the thruster power. Also as a part of this testing, PPU fault-protection responses for propellant flow starving were successfully demonstrated.

After the low-power mode validation, the PFCV control circuitry was exercised. The initial system-level test results indicated that circuit tuning was required to better accommodate the PFCV response and the gas-dynamic time delays between the PFCV and the thruster. The control loop reaction time was eventually slowed down by a factor of ten for the PFCV control circuit compared to the heritage thermothrottle circuitry. Additionally, it was found that the circuit filtering was insufficient to reduce the electrical noise from the thruster plasma breakdown at ignition to acceptable levels, so additional filtering was added. With these modifications, the system was operated at a range of nominal and stressing conditions including startups across the mission power range at different initial propellant flow rates (motivated by the PFCV open-loop control variability), throttling between different operating conditions, and discharge current perturbations during steady-state operation.

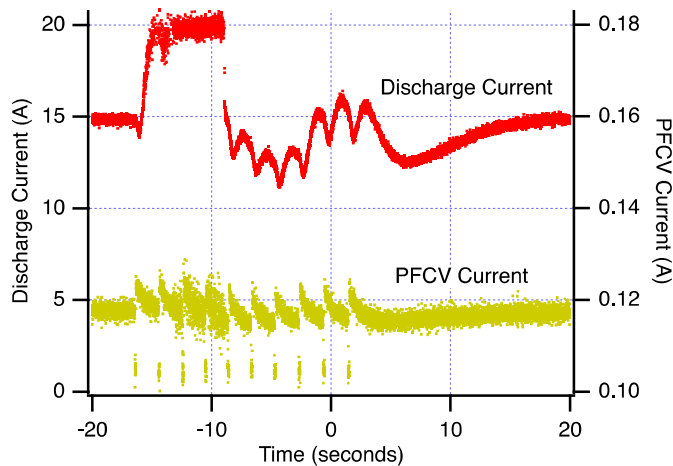


Fig. 9. PFCV Controller Perturbation Test.

(motivated by the observation in flight data of discharge current transients early in thruster life). The latter were induced in the test by short-duration changes in the PFCV control circuit; a series of these perturbations and the circuit response can be seen in Fig. 9. While operating at a steady 15 A discharge current, several perturbations were induced in a row, the first of which put the PPU discharge power supply into its current-limit mode. The control circuit responded to each perturbation by driving the discharge current back toward the nominal 15-A setpoint and recovered to that level within about 15 seconds of the last perturbation.

The system integrated test demonstrated all the required functionality and led to valuable insights into the PFCV response and control, especially during the thruster startup sequence. Tuning of the PPU control circuit was required to achieve the desired control responses, and some final fine-tuning is expected as all of the data are reviewed. Further details can be found in a companion paper.¹²

V. Thruster Performance Models

The Psyche mission design team uses a pair of thruster performance models (i.e. throttle curves) to perform trajectory analysis: thrust as a function of PPU input power and mass flow rate as a function of PPU input power. The throttle curves for Psyche have evolved throughout the project lifecycle as additional thruster performance data have been obtained. The first set of curves used for mission design in the proposal phase were prepared from SPT-140 DM4 data¹³ (later confirmed with the QM002 thruster¹⁴) and a simple model of the effects of facility pressure on thruster performance. The throttle curves presently used for trajectory analyses have improved significantly with the use of the flight thruster acceptance test data, improved knowledge of the effects of background pressure as a function of power, and the first set of Maxar flight data.

A. Acceptance Test Performance Data

Psyche's four SPT-140 thrusters have completed acceptance testing at the Fakel manufacturing facilities and been delivered to the Maxar facilities in Palo Alto, California. Each thruster went through the standard acceptance test (AT) procedure for Maxar's commercial product line with some additional tests added to cover Psyche mission-specific operating conditions. The standard set of tests included thruster operation over the nominal power range for commercial missions of 3.0 to 4.5 kW discharge power. Psyche added thruster performance tests at discharge powers of 0.9 and 1.0 kW and an additional thermal-vacuum cycle at 1.0 kW which included a thruster cold start and a hot start. The low-power performance tests were specifically included not just to measure overall thruster performance, but also to characterize the cathode performance and ensure it was in-family with the performance and life test results obtained on the qualification-model thrusters.

Thrust and propellant flow rate data for all four flight thrusters are shown in Fig. 10. The thrust was linear with power over the full range, with maximum unit-to-unit variations well within the measurement uncertainty of ± 2.5 mN. The propellant flow rates were slightly non-linear with power, but again with maximum unit-to-unit variations well within the measurement uncertainty of ± 0.25 mg/s for higher powers and ± 0.1 mg/s for the two lowest powers. All of these performance data were acquired in a test facility with relatively high background pressures (about 30-100 μ Torr calibrated on air), which is known to affect the measured performance.¹¹ Corrections for those effects are discussed in a later section of this paper.

For the two lowest power operating conditions the cathode keeper voltage, cathode-to-ground voltage, and the discharge current oscillations were examined and compared to low-power operation of the two qualification-model thrusters. All acceptance tests at these conditions were performed using the 9% cathode flow fraction and 1.15 A keeper current conditions selected for Psyche.¹¹ Although direct comparison of the results was complicated by some differing test conditions, the data in Table 2 show that the cathode-to-ground

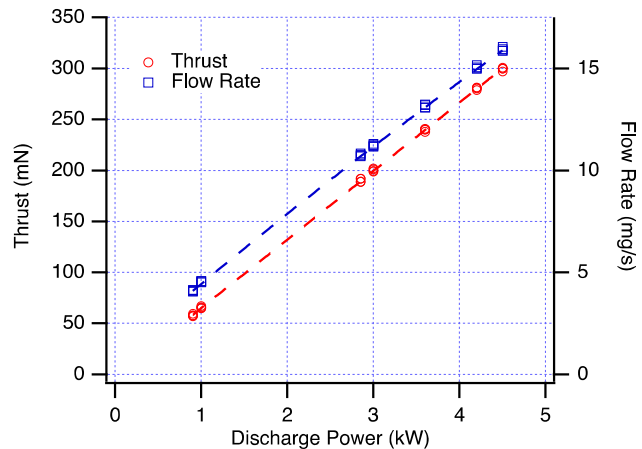


Fig. 10. Acceptance Test Performance Data for the Four Psyche Flight Thrusters.

voltages and discharge current oscillations were within family. The cathode keeper voltages were lower than observed in the other tests, but this could be due to the fact that these cathodes had very little operating time compared to the qualification model cathodes.

B. Maxar Spacecraft In-Flight Performance Data

Maxar completed its first long-duration electric orbit-raising (EOR) in

2018 using two SPT-140 thrusters, each of which operated at a discharge power of 4.0 kW. The EOR portion of the mission started at a 13,000 km perigee altitude following a bipropellant orbit-raising maneuver. The multi-month orbit-raising allowed for long-term trending of both thrust and flow rate. The on-orbit thrust results agreed favorably with pre-launch predictions based on the life-test data with an applied pressure correction. Total impulse delivered during the first week of EOR was 130 kN-sec with an estimated average thrust of 234 ± 0.5 mN per thruster. This corresponds to a thrust/power ratio of 58.5 mN/kW. The thrust value was assumed to be half of the calculated spacecraft thrust because two thrusters were firing, while the thrust uncertainty accounts for bipropellant and xenon mass uncertainties as well as curve-fitting uncertainties to the measured orbital parameters.

During this EOR the electric propulsion system applied a delta-V of 1059 m/s to the spacecraft, consuming 160 kg of xenon over the ten-week duration. No anomalous shutdowns of the system occurred; however, the thrusters were cycled thirty-six times for eclipses and completed the final six weeks at a 100% duty cycle. The thrust prediction was refined over the course of the orbit raising. A final thrust prediction was uploaded seven days prior to completion of EOR, and notably no bipropellant firings were required for spacecraft capture into the allocated geostationary orbital slot. The data from this orbit-raising campaign has provided important information for and also confidence in the thruster performance models for Psyche mission needs. A complete summary of this EOR mission and the thruster performance results will be provided in a forthcoming paper.²⁹

C. Throttle Curve Development

The performance of the SPT-140 thruster is known to be a function of both facility background pressure and thruster operating duration. These effects have been measured separately using two different qualification-model thrusters, and need to be taken into account when developing the throttle curves. In general, the effect of pressure on performance could be different at the beginning of life, after 800 hours of life (i.e. the point at which the existing pressure-effects data were collected¹¹), and after several thousand hours of life. At this time, it is assumed that the pressure effects and aging effects on thruster performance may be treated as separable effects.

The pressure-effects testing conducted on the SPT-140 provided new information on the magnitude and behavior of the effects of pressure on performance at different thruster power levels.¹¹ At the maximum thruster discharge power of 4.5 kW the absolute thrust change with pressure was the greatest. In addition, thrust decreased continuously down to the lowest obtainable facility pressure and did not asymptote to a constant thrust level, leaving a significant uncertainty in the extrapolation of thrust to space vacuum conditions. At the lowest thruster power of 0.9 kW there was no measurable change in thrust with pressure, indicating that the same thrust would be observed in space. At the intermediate power levels the magnitude of the thrust change with pressure decreased with power.

Until recently there has been a lack of a rigorous first-principles explanation of the effects of pressure on thruster performance. Although significant improvements in understanding the phenomena that drive this effect have been made,^{16,17} there are still large uncertainties with computing the thrust magnitude in space conditions for the SPT-140. Hence, in-space thrust measurements are needed in combination with the ground-based pressure-effects testing to predict thruster performance. Fortunately, recent flight performance data for the SPT-140 have been obtained as described earlier and these data can be used to reduce the uncertainties in the method used to correct for facility pressure. With the knowledge of the acceptance test data for those EOR thrusters, the magnitude of the pressure correction to in-flight thrust at the 4.0 kW operating point was determined to be -31 mN.

The ground-based pressure-effects data can be used to take this correction factor which was obtained at a single power level and extend that to the full range of powers required for Psyche. Empirical examination of the ground-based data suggest that a quadratic power law could adequately describe the thrust difference between that measured in the Fakel acceptance test facility and that expected in space as a function of power. Using the pressure correction

Table 2. Low-Power Cathode Performance Characterization Data.

Parameter	Measured Value				In-Family Range Based on Previous Testing
	Psyche FM029	Psyche FM030	Psyche FM031	Psyche FM032	
Cathode-to-Ground Voltage, V	-29.2	-28.5	-27.3	-28.9	-24 to -32
Cathode Keeper Voltage, V	17.8	18.3	16.5	17.3	20 to 25
Discharge Current Oscillations, A RMS	0.3	0.3	0.3	0.3	0.05 to 1.7

factor for the 4.0 kW power level and the assumed quadratic power law scaling, an estimate of in-space performance can be determined as a function of power. Finally, that pressure correction can be applied to the Psyche thruster acceptance test data to give a beginning-of-life in-space thrust prediction for the Psyche thrusters. This method

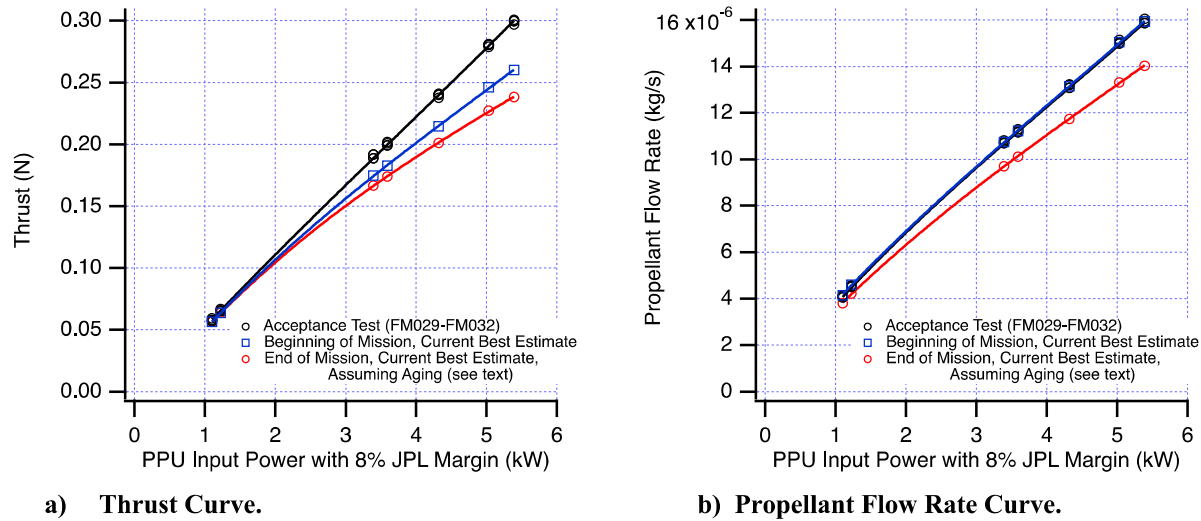


Fig. 11. Current-Best-Estimate Throttle Curves for Mission Design.

predicts a pressure correction of -39 mN and a beginning-of-life in-space thrust of ~260 mN at a 4.5 kW thruster discharge power for Psyche. The difference between the acceptance test data and the beginning-of-mission in-space thrust prediction can be seen in Fig. 11a.

The effects of thruster operating duration on performance over long time periods are known only from the thruster life test (discussed later in Section VI.B), roughly 90% of which was performed at a thruster power of 4.5 kW. In that test the thrust at 4.5 kW decreased by about 8% over the first 2,000 hours of operation and then stayed roughly constant through the 6,000 hour point⁹ to the 10,000 hour point.⁷ Although performance data were also acquired at a power of 3.0 kW at regular intervals, since most of the test was operated at 4.5 kW those data likely do not reflect the evolution of performance at a constant power of 3.0 kW. Thruster aging effects at a discharge power of 0.9 kW can be inferred from the set of thrust data shown in Table 3. Measured thrust for six different thrusters, acquired at beginning-of-life conditions and after thousands of hours of operation and at two different facilities pressures, are all within the measurement uncertainty. These results indicate that background pressure and thruster aging have a small or negligible effect on thrust at this power level. The Psyche throttle curve development makes this assumption, and also assumes that the thrust decrease due to aging is linear with discharge power. The difference between the beginning-of-mission and end-of-mission thrust using these assumptions can be seen in Fig. 11a.

Ideally the thrust change with time at each power level would be incorporated into trajectory analysis software but the tools do not presently have that capability. Instead, the mission design team has elected to apply the thrust aging correction at the beginning of life as a conservatism. Alternate methods of incorporating the aging correction are under investigation.

The preceding discussion has focused on thrust performance but a similar method can be used for mass flow rate performance. The pressure-effects data¹¹ indicate that there is no flow dependence on background pressure except for a ~1% effect at the lowest powers. Life test data indicate a flow reduction of ~12% over the course of

Table 3. Measured Thrust at 0.9 kW Discharge Power for Several SPT-140 Thrusters and Test Conditions.

Thruster	Thruster Age, hours	Facility Background Pressure, μTorr (Xe)	Measured Thrust, mN
QM002	~790	~1	57 ± 2
	~9,400		58 ± 5
QM001	~9,900	~10	54 ± 5
	~10,400		55 ± 5
Psyche FM029	~40	~10	58 ± 5
Psyche FM030			60 ± 5
Psyche FM031			58 ± 5
Psyche FM032			57 ± 5

the test at 4.5 kW (see Section VI.B). Analysis of 0.9 kW performance data suggest a flow rate reduction of ~7% from beginning-of-life to 10,000 hours and a linear relationship with discharge power was again assumed. The pressure and aging corrections for propellant flow rate can be seen in Fig. 11b.

Finally, the thruster throttle curves are based on PPU input power with a specified power margin. The curves use the PPU efficiency specification developed for Psyche, which was based on engineering-model efficiency measurements with margin added to account for the full range of expected PPU environments and power bus input conditions – the total efficiency ranges from 89.2% to 92.9% over the full range of thruster powers. The PPU input power is determined from these efficiencies and the total thruster power, which includes the magnet power and keeper power as well as the discharge power. Power margin is also added to the throttle curves to account for propulsion and power subsystem uncertainties at the system level.⁵ During the proposal phase and early mission development this margin was 15%, and was reduced after project PDR to 8%.

Current-best-estimate throttle curves for thrust and propellant flow rate are shown in Fig. 11 along with the acceptance test data for the four Psyche thrusters. The beginning-of-mission cases reflect the application of the pressure corrections described earlier to the mean of the acceptance test data. The end-of-mission cases assume full-power thrust and flow rate degradations as observed at the end of the thruster life test, also described earlier, as applied to the beginning-of-mission curves. The mission design team mostly uses the end-of-mission curves for trajectory analysis instead of trying to model performance changes with time throughout the mission. Multiple sets of throttle curves have been created for additional trajectory analyses, including those that include worst-case thruster performance assumptions and some that account for performance changes at interims between beginning-of-mission and end-of-mission. Throttle curve refinement will continue as additional in-flight data are collected from upcoming Maxar missions and trajectory analyses and trade studies are completed.

VI. Thruster Life Validation

The SPT-140 lifetime has been validated for commercial missions in part by the thruster life test. The Psyche mission also relies heavily on the life test for thruster life validation, even though the mission profile is significantly different than for a commercial mission. In this section the mission requirements for thruster life are reviewed, a summary of the thruster life test is provided, and the results of thruster wear simulations for a representative mission profile are presented.

A. Mission Requirements for Thruster Life

The JPL institutional requirement for electric thruster life is that thrusters must demonstrate by test a total impulse capability of 100% of the planned worst-case mission usage. In addition, a total impulse margin of 50% is required and that margin may be demonstrated by either test or analysis. Therefore, thruster life requirements for the Psyche mission must be tabulated in terms of thruster impulse.

The impulse required from the electric propulsion subsystem for the baseline mission design at Project PDR is shown in Table 4 for each mission phase along with the propellant margin, which is *potentially* required impulse. Almost 90% of the total impulse is used just to get the spacecraft from launch vehicle separation to capture in the first science orbit. Transfers between science orbits and orbit maintenance account for just 2% (0.3 MN-sec) of the total. Impulses for the other, non-deterministic categories were all conservatively computed based on the present propellant allocations and thruster operation at full power. As mission development continues, it is likely that the deterministic impulses will change slightly as the spacecraft mass evolves and the thruster throttle curves are refined. Updates are also expected to the missed thrust and spacecraft commissioning allocations.

The total impulse requirement of 16.5 MN-sec in Table 4 is for the mission as a whole. Although the spacecraft will have four thrusters, the mission must

Table 4. Mission Total Impulse Requirements.

Mission Phase / Propellant Allocation	Impulse Required MN-sec
Deterministic Cruise Through Capture to Orbit A	14.5*
Cruise Momentum Management	0.1†
Asteroid Proximity Operations	0.3*
Spacecraft Initial Checkout/Commissioning	0.3†
Margin – Missed Thrust	0.6†
Margin – Thruster Performance Uncertainties	0.7†
Mission Total	16.5

*for baseline mission design at Project PDR.

† assumes all operation at 4.5 kW.

be tolerant to a single thruster failure so only three thrusters must be able to deliver this impulse. This equates to a per-thruster impulse requirement of 5.5 MN-sec. Per the JPL thruster life requirement, the SPT-140 must then demonstrate a minimum of 5.5 MN-sec of impulse by test and an additional 2.75 MN-sec by either test or analysis, for a total of 8.25 MN-sec.

The thrusters must also have demonstrated 150% of the required mission cycles. Preliminary estimates of the on/off cycles required for the mission have been made based on assumptions for mission operations. This total is about 1200 cycles for all thrusters and is dominated by a conservative assumption of daily thruster operations for momentum wheel unloading during the cruise phase. Again accounting for a single-fault tolerance, this equates to a per-thruster cycle requirement for the mission of 400 cycles and a demonstration by test of 600 cycles. This is much smaller than the 5,400 cycles actually demonstrated during the thruster life test, so the conservatism in the mission cycle estimate is not a significant concern.

B. Life Test Summary

The SPT-140 thruster life test was conducted in two phases: a main phase that was representative of thruster usage for a geostationary communications satellite, and a life test extension that supported the Psyche mission by operating first at low powers and then at full power until a propellant throughput of 500 kg had been achieved.^{7,9} The life test was performed with the Qualification Model 001 (QM001) thruster at Fakel's test facilities, where the test chamber background pressure was $\sim 1.5 \times 10^{-6}$ Torr (calibrated on air) when the thruster was operating at full power. Prior to the life test QM001 had been subjected to a full acceptance test including environmental testing.

The main phase of the life test was performed at thruster discharge powers of 4.5 and 3.0 kW, representing the electric-orbit-raising and station-keeping portions of the commercial mission, respectively. Roughly 90% of the operating time in this phase was spent at the 4.5 kW power level. The main phase was completed in 2015 with a propellant throughput of 468 kg, total impulse of 8.3 MN-s, and an operating duration of ~ 9300 hours.

The life test extension for Psyche was performed for 250 hours at a thruster discharge power of 1.0 kW, another 250 hours at 0.9 kW, and an additional ~ 480 hours of operation at 4.5 kW. The low-power thruster operating conditions included a cathode keeper current of 1.15 A and a cathode flow fraction of 9%. At the conclusion of the life test extension, the thruster had been operated for 10,371 hours with a total propellant throughput of 500 kg and a total impulse of 8.79 MN-sec. This total impulse is about 160% of the mission-required 5.5 MN-sec total impulse for each thruster, thus meeting the JPL institutional requirement for demonstrated thruster life. In addition, over 5,400 on/off cycles were accumulated which far exceeds the mission cycle requirement.

Thrust data obtained during the life test for the full-power operating condition are shown in Fig. 12. Thrust decreased by about 8% over the first 2,000 hours of the test and then was roughly constant for the remainder of the test (with a notable excursion near 3,000 hours). The propellant flow rate also decreased over life as seen in Fig. 13, falling by about 12% by 9,300 hours. The measured flow rate at the end of the life test extension was about 14% lower than the beginning-of-life value.

Thrust was not measured *in situ* during the life test extension but rather at three separate reference performance tests: before and after the low-power operation, and at the conclusion of the test. Those

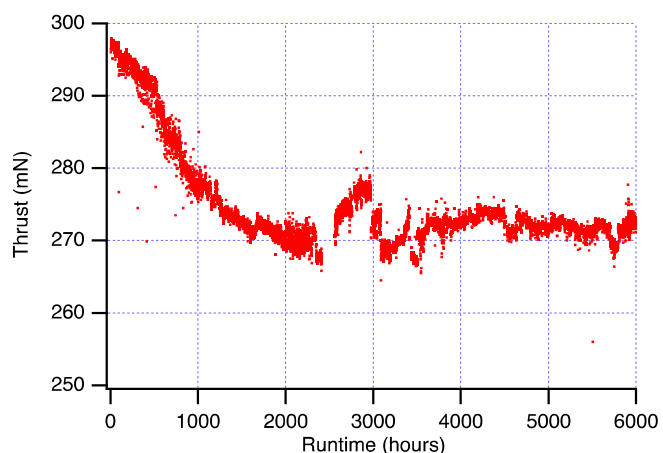


Fig. 12. Measured Thrust at 4.5 kW Thruster Discharge Power.

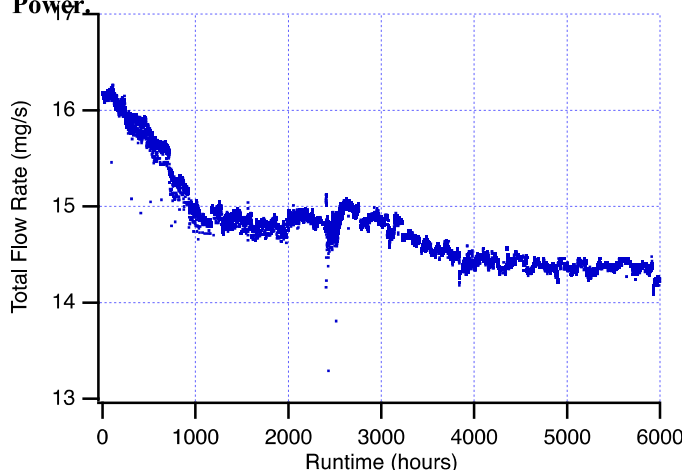


Fig. 13. Measured Total Flow Rate at 4.5 kW Thruster Discharge Power.